ANCIENT METEOROLOGICAL OPTICS*

Abstract: Presocratic, Peripatetic, Epicurean and Stoic theories that aimed to explain Aristotle's four fundamental phenomena of meteorological optics are compared with one another and with modern theories. Notable recorded instances of these and associated phenomena are cataloged. Aristotle's streak, Octavian's halo, Vitellius' antisun and Constantine's and Cyril's crosses are identified.

Ancient literature abounds in references to the phenomena of meteorological optics. In earliest times, these phenomena were grouped in isolated categories—such as rainbows—and given a mythological or religious interpretation, as in Homer or Genesis 9. After the Ionian Greeks began to speculate scientifically in the 6th century BC, physical theories about rainbows and other meteorological phenomena came into vogue, starting with Anaximenes' doctrine about the rarefaction of air into fire and its condensation into clouds and then water. Anaxagoras and others built on this foundation, but it remained for Aristotle to effectively define the field Plato had called "meteorology" and to offer consistent theories of its divisions, including one containing all the "non-fiery" optical phenomena of the atmosphere.

Aristotle, however, discussed meteorological optics separately from mathematical and physical optics, although he knew the essential links and provided occasional geometrical demonstrations of ray propagation as illustrations of reflection.[1] Consequently, the subject never became mathematical in the way that astronomy, optics, harmonics and statics did. Aristotle and most who followed him combined four fundamental phenomena of meteorological optics under a single umbrella: halo, rainbow, mock sun and streak. Although the common denominator in Aristotle's comprehensive theoretical explanation was reflection from a moist cloud, his concept of reflection was not universally accepted.

A number of modern authors have traced the development of ancient meteorological optics, focusing primarily on how the ancients explained the phenomena and less on comparisons with modern observations and theories. Some of these comparisons in the

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[1] Arist. *APo.* 79^{a}10–13, 98^{a}26–9; *Ph.* 194^{a}8–12; *Mete.* 3. Fiery (i.e., real) and nonfiery (i.e., illusionary) optical phenomena were first formally differentiated by Posidonius; see Waiblinger (1977) 27.

older studies are now out of date. Furthermore, modern authors have concentrated on the rainbow (as did the ancients) with less attention directed to the other phenomena. Finally, all authors have essentially ignored the specific instances recorded as prodigies and portents in antiquity.[2]

In order to not cover ground already adequately trodden, my focus will be on the halo, mock sun and streak, along with two closely allied phenomena, the light cross and mock moon, which were not discussed by Aristotle. Unlike the rainbow, these are all parhelic and paraselenic phenomena of the upper atmosphere, and so form a natural physical group in today's understanding of such phenomena. To orient the reader, a synopsis of modern meteorological optics is presented first in a non-technical format. The ancient theories follow, with the rainbow included for necessary comparison. Finally, the specifically reported optical displays with historical interest are collected and discussed.

A. Primer of Meteorological Optics

The atmosphere is conventionally divided into three parts: a lower part called the *troposphere*, where our ordinary turbulent weather and clouds occur; a middle part called the *stratosphere*, where tiny particles of dust remain quietly suspended for years; and a tenuous upper part, which does not concern us here. Within the troposphere, the higher layers are very cold, and ice crystals form in them, creating cirrus clouds. Occasionally, when a violent volcanic eruption thrusts its ejecta far aloft, the stratosphere becomes filled with very fine particles composed of silicate ash and sulfate aerosols. Although the heavier ash falls out quickly, the aerosols can survive for several months to a few years.

The particles that cause the peculiar optical effects thus occupy characteristic parts of the atmosphere. Water droplets occur in the lower layers of the troposphere. When sunshine penetrates a water droplet, the rays are first refracted at the surface, then reflected from the backside and finally refracted again on leaving the surface. This causes a *rainbow* to appear opposite the sun for any observer. Ice crystals and volcanic dust, higher in the atmosphere, diffract the sun's light and create what is known as a *corona* or *aureole* around the sun. The corona due to volcanic dust is called a Bishop's ring.[3] Rain-

[2] The most important work on the subject is Ideler (1832) 180–99; Gilbert (1907) 600–18; Boyer (1959) 33–73; Böker (1962) 1663–92; Taub (2003) 71–164. See also the brief account by Blay (1995) 14–20. My general approach to the subject is like that of most of these authors, in that I do not attempt to place meteorological optics within the larger picture of ancient science. My discussion sets it instead in the context of its time, lists ancient instances of the phenomena and discusses them in the light of modern knowledge. Since science is cumulative and never definitive, and observational data remain valuable, this practical approach using a modern viewpoint has its place.

[3] First described by Bishop (1884) after the Krakatau eruption of 1883.

bows and diffraction coronae are red on the outside and blue on the inside of their arcs. But ice crystals can also refract light, in which case they form a circular *halo* around the sun. Radial spokes and tangent arcs occasionally accompany the halo, creating an irregular appearance. A refraction halo differs from a diffraction corona in being blue on the outside and red on the inside.[4] All these particles also reflect light to some extent. In this case, the reflected light remains colorless (that is, white) if the unobscured sun is the source of it.

Refraction from ice crystals can sometimes produce a white *light pillar* rising above and extending below the sun. At the high point where the pillar intersects the halo, another light enhancement, called the *vertical parhelion*, may occur. The light pillar is often accompanied by a horizontal crossbar, another reflection effect. The combined pillar and crossbar yield a *light cross*, centered on the sun. Thus whenever the halo is invisible, only the cross of light appears.[5]

A full display of the optical effects produced by the rising and setting sun can be very impressive. Especially when the sun lies close to the horizon, it generates a faintly visible circle around the whole horizon at the same elevation, called the *parhelic circle*. In the antisolar position, a weak luminous patch may occur, the so-called *anthelion*. Both the parhelic circle and the anthelion appear white because they are caused by reflected sunlight. The multicolored refraction halo around the sun intersects the white parhelic circle at two points, situated about 22° north and south of the sun. At these points, enhancements of light occur, commonly designated *mock suns*, *sundogs* or *parhelia*. Sometimes only one parhelion appears, while on rare occasions a second halo (or even a diffraction corona) of radius 46° can be seen, accompanied by its own parhelia. Like the refraction halo from which it is formed, a parhelion at 22° is red on the side facing the sun. A mock sun can be exceedingly bright, sometimes as bright as the real sun, in which case it appears entirely white and colorless. Even rarer phenomena have been reported, but these need not be discussed here.[6]

[4] Humphreys (1940) 476, 512, 552, 555; Minnaert (1940) 172, 192, 214, 282. Color photographs of these phenomena appear at Greenler (1980); Meinel and Meinel (1983); Lynch and Livingston (1995). Refraction is the bending of light rays as they pass through a partly transparent medium, whereas diffraction is the bending of light waves around an opaque object; the scattering of the white light disperses the light into a spectrum. These phenomena are most simply described by geometrical optics—an idealization that nevertheless does not really account for diffraction. All of them, however, should be consequences of Maxwell's laws of electromagnetism.

[5] Vertical parhelion: Humphreys (1940) 536, 544. Light cross: Humphreys (1940) 543–5; Minnaert (1940) 201–3. Photograph of light cross: Fiorino (2007) 37.

[6] General discussions: Humphreys (1940) 501–45; Minnaert (1940) 190–204. Photographs as follows. Parhelic circle: Fiorino (2007) 37. Anthelion: Humphreys (1940) 538. Double halo: Lynch and Livingston (1995) 157. Mock sun: Fiorino (2007) 37.

Similar optical features are associated with the moon. Rainbows, coronae, haloes, light crosses and mock moons (also called *moondogs* and *paraselenae*) are seen when the moon is very bright, at or near full.[7] Owing to the general faintness of moonlight, however, more complex phenomena are rarely observed. Faint coronae can also be observed around the brighter planets and stars.

B. Ancient Theories

Which among the phenomena of meteorological optics first received theoretical attention in antiquity is unknown. Although the rainbow is attested first, Aristotle himself discussed the halo before the rainbow in his *Meteorologica* because this arrangement suited his theoretical requirements. Since we are not constrained by Aristotle's pedagogical considerations, I follow the probable chronological order. To simplify the discussion, no exposition of ancient theories of vision is included, since the basic physics of the meteorological phenomena remains the same whether the line of sight proceeds from the eye to the object or vice versa. In the *Meteorologica* (but not elsewhere) Aristotle adopted an extromission theory of vision.

Rainbow

Greek writers called the rainbow *iris* or (rarely) *toxon*, while Latin writers referred to it as *arcus*. Although speculation about the origin of the rainbow goes back to early myths, Anaximenes' explanation is the first scientific one of which we have a record. He believed that the rainbow is generated by the sun's white rays of light falling on an impenetrably thick, dark cloud; the mixture of white and black produces the other colors. This view influenced all subsequent work throughout classical antiquity. Among known pre-Aristotelian thinkers, Xenophanes, Anaxagoras and Metrodorus of Chios accepted Anaximenes' idea. In particular, Anaxagoras added the important concept of reflection of the sunlight from the thick cloud as if from a mirror. Metrodorus believed that the sunshine brought out a blue color in the cloud and reddened the sunlight at its edges.[8] Although the problem of the curvature of the rainbow is not addressed in our sources, Boyer has reasonably concluded that the Presocratics envisaged a cloud of spherical shape.[9]

Aristotle presented the first detailed model, consisting of a thick cloud composed of dense air beginning to turn into water. The partially formed water droplets act as tiny mirrors that reflect color, because they are very small, but not shape, which only a large mirror can do. Nevertheless, the aggregate of water droplets behaves like a

[7] A painting by L. Wenckebach that shows many of these lunar phenomena in a full display is reproduced at Minnaert (1940) plate IX(b).

[8] Anaximen.: Aët. 3.5; Hippol. *Haer*. 1.6; Scholiast to Arat. 940. Xenoph.: 21 B 32 D–K. Anaxag.: Aët. 3.5; 59 B 19 D–K. Metrod. Chios: Aët. 3.5; Scholiast to Arat. 940.

[9] Boyer (1959) 42, 57.

smooth surface. Water, being dark, reflects a red color—hence the red on the outside edge of the rainbow arc. The green and blue are due to an even darker reflection on the inside edge. Yellow is an illusionary appearance due to contrast. The rainbow displays a relatively short arc because it lies far from the illuminating sun, in a direction opposite the viewer. Aristotle provided a geometrical demonstration of this relative positioning. He was aware of double rainbows and of rare lunar rainbows. He most likely knew the law of equal angles of incidence and reflection in the phenomenon of reflection from a plane surface. He also gave examples of refraction in air and water from familiar terrestrial situations, but did not apply this knowledge to a meteorological explanation of the rainbow and related phenomena. These he treated together as manifestations of reflection from a dense cloud containing different ratios of water and air.[10]

Most known post-Aristotelian authorities, including the founder of the Stoic school, Zeno of Citium, accepted Aristotle's theory of the rainbow, although with different emphases, minor variations and embellishments. Epicurus, in a typically contrarian way, agreed that the rainbow might be colored and shaped in the Aristotelian fashion, but then suggested that light might instead mix with air to produce colors in the air by some kind of reflection, while the circularity of the rainbow might come about if there were reflecting atoms (rather than Aristotle's water droplets) in the air or in the cloud and if they had emanated from the sun, which is round.[11] Posidonius and certain other Stoics, including apparently Artemidorus of Parium, argued that the rainbow arises because the sun's light bounces off a smooth, concave, mirror-like cloud. In Seneca's view, these Stoics were wrong to think that the cloud, which resembles a ball cut in half, reflects only a small segment of the sun rather than the whole solar image.[12] Although Seneca's own views are more like Aristotle's than like those of his fellow Stoics, in that he emphasized the reflecting properties of the water droplets forming the rainbow, he seems to have regarded the rainbow arc as the magnified image of the sun's circular shape, and confused the phenomena of reflection and refraction, thinking the latter to be a manifestation of the former. Finally, he believed that rainbows are prognosticators of weather—a very old idea, although Pliny doubted its validity.[13]

[10] Arist. *Mete*. 371^{b}18–7^{a}28; Sen. *Nat*. 1.3.5–8; Aët. 3.5; Scholiast to Arat. 940; Alex. Aphr. *in Mete*. *ad loc*.; Stob. 1.30; Olymp. *in Mete*. *ad loc*. A contemporary of Aristotle belonging to Plato's circle, Philip of Opus, supported the analogy of a mirror by noticing that the rainbow appears to follow the moving viewer (Alex. Aphr. *ad* 373^{b}32).

[11] D.L. 10.109–10. Lucr. 6.524–6 gives only Epicurus' first (Aristotelian) explanation.

[12] [Arist.] *Mu*. 395^{a}29–35; Sen. *Nat*. 1.4.1–4, 1.5.10–13, 1.8.4; Plu. *Mor*. 358f–9a; 765e–f; 921a; 937b; D.L. 7.152. The passage in pseudo-Aristotle reappears practically *verbatim* in Diogenes Laertius. Plin. *Nat*. 2.150 accepts the Stoic theory, but doubts that lunar rainbows occur, despite Aristotle, Posidonius and Seneca.

[13] Sen. *Nat*. 1.3.9, 1.4.1, 1.5.13, 1.6.5–6, 1.8.8; Plin. *Nat*. 2.150.

Seneca (*Nat*. 1.3.1–4) also discussed two other previously proposed explanations of the rainbow, without naming his sources. Perhaps these explanations were Epicurean but shorn of the objectionable atoms. One explanation is that the sun's rays illuminate an inhomogeneous cloud in such a way that the unevenness of the cloud's density produces light and shadow. Since it was often theorized in antiquity (for example, by Anaximenes) that all colors arise from a mixture of white and black, a rainbow will result. A second explanation is that the cloud contains a mixture of droplets of varying density, the less dense of which transmit sunlight and so are bright, while the more dense cast shadow. The mixture of types produces the rainbow's colors. Seneca thought of the cloud itself as having an intrinsic color (1.3.12–13, 1.5.11). Yet when the cloud is struck by sunlight, its water droplets yield all the colors, since bright light and dark light produce different colors. Although ancient authors recognized different primary colors of the rainbow, these apparent differences arise from subjective perceptions of the rainbow's true colors.

The late commentators Alexander of Aphrodisias and Olympiodorus the Younger elaborated on Aristotle's theory of the rainbow but added little new. Alexander did, however, note the darkness of the intermediate band that separates an outer rainbow from an inner one. We know from these authors, as well as from Seneca, that other writers seriously discussed refraction as a possible explanation of the rainbow, but details are lacking.[14]

Halo

A ring around the sun was designated by Greek writers as a *halôs*, *stephanos*, *iris* or (once) *kuklos*, while Latin authors wrote *corona*, *circulus*, *arcus*, *orbis*, *ambitus* or (once) *area*.[15] The word *halôs* means literally a threshing-floor, which was often circular in shape; it was accordingly translated into Latin as *area* (Sen. *Nat*. 1.2.3). Since no distinction seems to have been made among these terms, I have simply translated them all with the generic English "halo." Few ancient reports permit us to discriminate between the oppositely colored "refraction halo" and "diffraction corona," except occasionally when we can associate Bishop's ring with a volcanic eruption. Otherwise, the ancient likening of an observed "halo" to a rainbow implies only that some dispersion of colors was noticed.

[14] For a thorough discussion of Aristotle's reflection theory and of Alexander's and Olympiodorus' defenses of it, see Boyer (1959) 33–73. Boyer's lengthy discussion of the ancient rainbow remains valuable, but he can be inaccurate in places, depends occasionally on modern authorities as primary sources, and has some unexpected omissions (e.g., Epicurus).

[15] Arat. 796 initially uses *kuklos*, but follows this with *alôê* (*halôs*). Kidd (1997) 450–1, in spite of the explicit testimony of the scholia, Ach. Tat. 34 and Avienius 1484, insists that Aratus applied *kuklos* to the moon's disk rather than to a halo.

Aristotle noted that haloes are commonly seen around the sun, moon and bright stars. To him, a halo is the reflection of our vision off a large, uniform cloud of air and uncondensed water vapor, broken up into small parts that act like tiny mirrors. When the cloud surrounds its luminary evenly on all sides, the halo appears circular. But it is only weakly colored, or even uncolored, because the vapor has not yet turned into water and the luminary is very near. Aristotle's geometrical demonstration of the halo's circular shape, however, merely assumes what it sets out to prove, and he does not differentiate what we would call a "refraction halo" and a "diffraction corona" with their different spatial orderings of colors. The halo is always observed near but not too close to its luminary, because the luminary's heat dissolves the nearest parts of the cloud, while our vision becomes too weak if it has to travel far to reach the object. A dark halo around the sun or moon prognosticates rain, unless the halo is fading while still unbroken, in which case it is a harbinger of fair weather. If the halo is broken anywhere, it indicates wind from the quarter in which the break occurs.[16]

Epicurus is known to have discussed at least the lunar halo. In his theory, the moon's light reflects off the surrounding air, thereby forming the halo. Unlike Aristotle, Epicurus believed that the reflecting layer of air does not lie beneath the moon, surrounding it only in appearance, but that the body of air physically extends all the way up to the moon. We may conjecture that his theory of the solar halo would have followed suit, the sun being, in his empiricist view, only as large as it appears, namely about a foot wide! Posidonius, Seneca, Alexander of Aphrodisias and Alexander's teacher, Sosigenes, on the other hand, all accepted Aristotle's sublunary reflection theory. They were nearly alone; Alexander remarked that most other authorities ascribed the halo to refraction rather than reflection. Who these other thinkers are and what their arguments were is unknown.[17]

Seneca (*Nat.* 1.2, 1.10) provided a dynamic model for the halo that is different from Aristotle's static model. The rays of the sun or moon, he argues, strike and compress the air in a uniform way whenever the air is motionless.[18] Since the luminous source is spheri-

[16] Arist. *Mete.* 371^{b}18–26, 372^{b}12–3^{a}31, 374^{a}11–16; *Pr.* 15.12; Plin. *Nat.* 2.98; Alex. Aphr. *in Mete. ad loc.*; Stob. 1.30; Olymp. *in Mete. ad loc.* Weather prognostications later than Aristotle: [Thphr.] *Sign.* 22, 31, 51; Arat. 796–8, 811–17, 877–9 (with scholium), 941; Gem. 17.47; Ph. *On Providence* 2.47; Sen. *Nat.* 1.2; Plin. *Nat.* 18.344–9; Ptol. *Tetr.* 2.9, 2.13; Basil *Hexameron* 6.4; *Gp.* 1.3. Aratus states that two or three haloes presage even worse weather than one does; the redder or darker the halo, the worse the storm.

[17] Epicur. in D.L. 10.110–11; [Arist.] *Mu.* 395^{b}1–3; Sen. *Nat.* 1.2; Alex. Aphr. *in Mete. ad* 372^{b}34.

[18] Taub (2003) 164 considers that Theophrastus and Seneca, unlike Aristotle, thought of lunar haloes "as materially constituted, and not as optical phenomena." The slight evidence from Theophrastus (*Meteorologia*) is inconclusive, but Seneca clearly views the halo as an optical reflection of the luminary's light from a spherically

cal and the atmosphere is still, the halo too must be round, just as a pebble thrown into a fishpond creates many little circles in the water. Solar haloes are less common than lunar ones because the sun's light is often strong enough to disperse the thin daytime air. Starlight, on the other hand, is too feeble to form haloes around any but the brightest stars. Seneca perceived the halo basically as a complete, circular rainbow. Therefore, like Aristotle, he must have failed to note the reversed order of colors in what we would call a "refraction halo." Finally, Olympiodorus (*in Mete*. *ad* 372^{b}18) seems to have been the first to measure the halo's diameter, which he gave nearly correctly as 40°.

Mock Sun

Classical authors usually refer to a mock sun as a second *hêlios* or a second *sol*. Instances of two mock suns accompanying the real one are reported about as often as a single mock sun. Pliny (*Nat*. 2.99) states that more than three "suns" (two mock suns and the real sun) had never been recorded up to his time. A mock sun is also designated by pedagogical and technical authors as a *parêlion* or *anthêlion* owing to its sky position and brilliance.[19]

Anaxagoras explained the mock sun as he did the rainbow, as a mirrorlike reflection from a dense cloud. Aristotle added his own details. The mock sun is simply a strong reflection from a homogeneous, watery cloud. Since this type of cloud looks like a large uniform mirror and the cloud must be located close to the sun, the powerful reflection shows a single color—that of the real sun, white. A mock sun always appears to the side of the real one and usually around the time of sunrise or sunset. It does not occur above or below the sun or in the opposite quarter of the sky, for reasons like those given for the halo. Since the ambient air is saturated with water when a mock sun forms, the phenomenon always presages rain.[20]

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compressed mass of air; to him the halo is thus not a "real" material phenomenon like a substance emitting fire.

[19] The less common word *anthêlion* was employed by the Scholiast to Arat. 881, Cleom. 2.6.10, Aët. 3.6, Basil *Hexameron* 6.4 and others, although an ordinary mock sun is clearly being referred to. See Böker (1962) 1682–4; Goulet (1980) 5. Unaccountably, Böker treats the *clipeus* and *disceus* "comets" (Sen. *Nat.* 7.20.2; Plin. *Nat.* 2.89, 2.100) as mock suns; they are most likely meteoritic bolides. He also interprets other kinds of "comets" (because Aristotle did?) as purely meteorological phenomena; most seem to be genuine comets. Kidd (1988) 469 and Bowen and Todd (2004) 162 wrongly interpret the ancients' *anthêlion* as the modern anthelion.

[20] Anaxag. in Aët. 3.5; Arist. *Mete*. 371^{b}18–20, 372^{a}10–21, 377^{a}29–8^{a}14; *Pr*. 15.12; Plin. *Nat.* 2.99; Alex. Aphr. *in Mete. ad loc.*; Prud. *Origin of Sin* 85–8; Stob. 1.30; Olymp. *in Mete*. *ad loc*.; Lyd. *Ost*. 4. Weather prognostications later than Aristotle: [Thphr.] *Sign*. 22, 29; *Vent*. 36; Arat. 880–9; Sen. *Nat*. 1.13; Ptol. *Tetr*. 2.9; Basil *Hexameron* 6.4. Aratus says that two red mock suns presage a wintry storm; if there is only one of them and it lies to the north, a north wind will blow; and if only one of them occurs, to the south, rain will arrive from that direction.

Sporus (3rd century BC) and Posidonius seem to have mostly accepted Aristotle's theory of the mock sun, but they explicitly assumed a spherical cloud and emphasized its extreme whiteness due to its following the sun so closely. Although Strabo thought that a mock sun must be strongly heated by the sun's rays, the scholiast to Aratus 880–9 says that if the cloud is whipped by a cold wind, it freezes into solid ice and as a consequence of its higher density appears red when receiving the solar rays. Only Aratus claims that a mock sun must appear red in order to serve as a weather sign.

Seneca discussed multiple mock suns. Because clouds cannot receive a clear image of the sun if they are in motion, thin or filled with impurities, only one or two clouds at any time are likely to have enough coherence and density to reflect a good image of the sun. If there are two such clouds, one will reflect a secondary image from the other, yielding a pair of mock suns. Cleomedes later conjectured that a mock sun might be able to form above the sun after sunset, since the air near the horizon is both dense and moist. Ammianus Marcellinus, on the other hand, believed that a mock sun had to be a cloud lying very high up in the atmosphere, in close physical proximity to the sun. Different interpretations were possible because Aristotle was unclear about the vertical distance at which mock suns form.[21]

Streak

Aristotle associated the so-called streak or rod (*rhabdos*, Latin *virga*) with the halo, rainbow and mock sun in a common origin, but specifically with the mock sun in its physical development. The streak appears to the side of the sun around sunrise or sunset. It is caused by light reflection from an inhomogeneous cloud, in contrast to the homogenous cloud that leads to a mock sun. The small inhomogeneities reflect the colors of the sun and not its shape, and so the manifestation is a kind of "straight rainbow" rather than a white circular patch. As in the case of the mock sun, the streak cannot develop very close to or very far from the sun. Also like a mock sun, it portends rain, especially when it occurs south of the sun.

Aristotle's views were endorsed and reproduced by the anonymous authors of *De mundo* and *De signis*, as well as by Seneca, Aëtius, Ptolemy, Alexander of Aphrodisias, Basil, Stobaeus and Olympiodorus.[22] According to Seneca (*Nat*. 1.11.1), another class of streak looks like a bundle of thin rays extending through narrow openings in the clouds. Seneca's description thus implies that the

[21] Posidonius and Sporus in Scholiast to Arat. 881; Str. 7.3.18; Sen. *Nat.* 1.11–13; Cleom. 2.6.10; Amm. 20.3.6. Aristotle's confusing stratification of the sublunary sky has been deciphered by Lee (1952) 24–7, 243, 250–1; as well as by Seneca (*Nat.* 2.10), as Williams (2005) 155 has noted.

[22] Arist. *Mete*. 371^{b}19, 372^{a}10–14, 374^{a}16–18, 377^{a}27–8^{a}11; [Arist.] *Mu*. 395^{a}29–36; [Thphr.] *Sign*. 11; Sen. *Nat.* 1.9–10; Aët. 3.6; Ptol. *Tetr*. 2.9; Alex. Aphr. *in Mete*. *ad loc.*; Basil *Hexameron* 6.4; Stob. 1.30; Olymp. *in Mete*. *ad loc.*

term "streak" came in time to be employed more broadly than in Aristotle. The original sources used by Aristotle are unknown, although the offhand way in which he introduces *rhabdos* suggests that the word was already familiar as a meteorological term.

Modern authors such as Carl Boyer and Robert Böker agree with Otto Gilbert in interpreting Aristotle's streak as a watergall (or weathergall), which is simply the truncated lower portion of a rainbow, while Jules Tricot and Liba Taub regard the term as referring to a luminous column rising above the sun. Aristotle, however, placed the streak close to the sun not opposite it, and to the side of the sun, not above it. David Sider and Carl Brunschön suggested that a streak is a light pillar extending above and below a mock sun, but the rainbow colors are then difficult to understand. More credible is Paul Oltramare's suggestion of a long horizontal band, the parhelic circle. But this circle is white, not colored like a rainbow. Pierre Louis has conceived of a patch of oblong striations having the colors of a rainbow, but his reworking of Aristotle's description does not identify the streak. I suggest that the streak is simply a multicolored mock sun. Whenever a mock sun is not formed in the shape of a circle, it can display a coarse, diamond shape with edges colored like a rainbow. In its purest form, the whole object looks like a small, rectilinear rainbow.[23]

C. Specific Appearances

Some phenomena such as rainbows and lunar haloes are so frequently seen that they are not reported in ancient literature as special prodigies even though they were usually regarded as weather signs. Other phenomena, not so common, include solar haloes, mock suns and light crosses. Whenever they are recorded, they must have been either strikingly conspicuous owing to an extremely unusual atmospheric condition or ominously associated with an important event. The rarest phenomena of all, such as bright mock moons, must have been infrequently noticed.

Solar Haloes

Haloes surrounding the sun were recorded in antiquity in conformity with these expectations. Surviving reports are summarized in Table 1. The rainbow-like haloes of 121 and 44 BC were almost certainly Bishop's rings due to eruptions of Mount Etna in 122 and 44 BC.[24] But it was Octavian's entry into Rome in 44 BC that made his

[23] Gilbert (1907) 617; Tricot (1941) 185; Boyer (1959) 25; Böker (1962) 1684–5; Oltramare (1973) 37; Louis (1982) 6; Taub (2003) 78. The pure, rainbow-like mock sun is illustrated at Lynch and Livingston (1995) 162, and imperfectly at Fiorino (2007) 37. The second type of streak in Seneca's description, if it too is colored like a rainbow, may be a cirrus-cloud display viewed through breaks in cumulus clouds, as illustrated at Gonnelli (2008) 12.

[24] Stothers and Rampino (1983) 6359. The halo of 44 BC has been dated with greater precision to the early part of May by Ramsey and Licht (1997) 101.

solar halo so memorable, because it appeared to encircle him like a kind of crown. The four other early reports of haloes might also be traceable to volcanic eruptions, but we do not know for certain. Since all these reports are found in the annual Roman prodigy lists, no special historical event need be attached to them. The haloes of 203 and 147 BC are noteworthy for having been visibly double.[25] The object of 203 BC consisted of a thin, rainbow-like inner halo and a wide outer halo of unspecified color, while the object of 147 BC was described simply as composed of a red halo and a white halo. The single halo of 90 BC also was red. No details are given for the halo of 114 BC.

Philostratus relates that a halo (*stephanos*) colored like a rainbow was seen in Greece by many people, including the provincial governor, ca. AD 94. Although his report appears in a biography of Apollonius of Tyana and he has chosen his meteorological terminology in clear allusion to the name of the emperor Domitian's assassin, Stephanus, there is no good reason to reject the report. By contrast, the biographer of Severus Alexander in the *Historia Augusta* says that among the many omens attending Alexander's birth in AD 208 was a halo surrounding the sun; even if authentic, this halo need not have been otherwise remarkable. Nor are any details known about the halo observed in AD 270, probably at Alexandria, which was later speculatively linked to the death of Claudius Gothicus at Sirmium.

Light Crosses

It is surely significant that our earliest surviving record of a light cross (*stauros*, *crux*) harks from the Christian era. But appearances of this type must have been noticed in previous centuries.

The luminous cross reported to Eusebius by Constantine the Great as having appeared to him and his army early in AD 312—almost certainly in Italy—has been attributed by modern scholars to a formation of clouds, shafts of sunlight, lightning or a parhelic display. There is no compelling reason to doubt Eusebius' account, which was quoted by many later authors. The reported location of the cross, "situated over the sun" (*huperkeimenon tou hêliou*), suggests a parhelic light cross.[26]

Very different circumstances are recorded for the luminous cross that appeared to many people in Jerusalem on 7 May, probably in AD 351.[27] According to St. Cyril, patriarch of Jerusalem, who was an eyewitness, the cross extended from Mount Calvary to the Mount of Olives in the eastern sky and appeared brighter than the sun. Philostorgius and the *Chronicon Paschale* mention that it was surrounded

[25] The double halo of 203 BC appeared during a period of suspected activity of local Italian volcanoes—specifically Vesuvius—extending from 217 BC: Stothers and Rampino (1983) 6360; Stothers (2002); to 202 BC: Krauss (1930) 69.

[26] Ideler (1836) 320–1 and Jones (1948) 95–6 likewise favor a light cross.

[27] Ramsey (2006) 207–11.

by a rainbow-like halo. Many other chroniclers report the cross, but not always the halo. This phenomenon illustrates what is probably the full development of a solar refraction halo enclosing a brilliant light pillar transected by the parhelic circle.[28]

Mock Suns

Euripides in his *Bacchae* has Pentheus claim to see two suns. Pentheus is insane, and also perceives two cities of Thebes.[29] Nonetheless, Euripides' mention of two suns may be rooted in the already well-known phenomenon of the mock sun. For example, John Lydus (*Ost*. 4) relates from an unknown source that an apparent doubling of the sun was observed when Cambyses invaded Egypt in 525 BC. Aristotle in his discussion of mock suns mentions that two suns once accompanied the real sun all day long in the Bosporus.[30] They were also said to be commonly seen in Pontus.[31]

A series of eight recorded instances of double or triple suns appear in the Roman prodigy lists, as summarized in Table 2. All these manifestations were reported at Rome or elsewhere in central Italy during the period 206–104 BC, except for one in Gaul in 122 BC.[32] Another five reports were made at Rome between 44 BC and AD 193 in connection with later, obviously important historical events. In the immediate aftermath of Caesar's assassination in 44 BC, a display of three suns appeared on two occasions. The first display occurred in 44 BC itself and involved a spiky halo surrounding the "lowest sun" (*solem imum*)—presumably the central, or real sun. The second display occurred in 42 BC, but no details are known.[33] Claudius' fifth consulship in AD 51 also witnessed three suns. Somewhat later, if Cassius Dio is to be believed, two suns in AD 69 portended Vitellius'

[28] Ezekiel (1; 3; 10; 11), who was living near Babylon ca. 593 BC, saw visions of wheels accompanied by strange animal figures in the sky. Although the whole context of his account as well as specific passages (1:1; 8:1–4; 10:22; 11:24; 40:1–2) suggest vivid dreams, possibly in a trance state, Menzel (1953) 125–34 interprets his visions as observations of a full parhelic display, the wheels being bright solar haloes and the animal figures being light pillars and crosses. Silverman (2006) prefers an auroral interpretation.

[29] E. *Ba*. 918–19; V. *Aen*. 4.469–70; Plu. *Mor*. 1083e–f; Clem. Al. *Protr*. 12; *Paed*. 2.24; Serv. *Aen*. *ad* 4.470; Nonn. 46.125.

[30] Arist. *Mete*. 372^{a}14–16; Str. 7.3.18; Plin. *Nat*. 2.99; Alex. Aphr. *in Mete*. *ad loc*.

[31] Anaxag. in Aët. 3.5; Cleom. 2.6.10.

[32] Rawson (1971) 160–1 points out that repetitions of prodigies, referred to as doublets, crop up occasionally in the Roman prodigy lists for different (but neighboring) years. Three doublets occur in Livy's lists for 206 and 204 BC (28.11.2–4; 29.14.3). Among them is a doublet of *duo soles*, to which I have assigned the year 206. The *duo soles* of 166 and 163 BC also may be a doublet. Ramsey (2006) 194 takes the second *sol* of 163 BC to have been a comet, under the mistaken belief that mock suns must always appear in pairs. Krauss (1930) 72 argues that the two daytime "moons" of 217 BC at Capena (Liv. 22.1.10) were faint mock suns. Finally, Kidd (1988) 468 appears to have mistaken the general phenomenon of "three suns" for three mock suns.

[33] Although Eus.-Jerome *Chronicle* Olymp. 184 seems to refer to the instance of "three suns" in 44 BC, comparison with Obseq. 68 and 70 shows that the apparition of 42 BC is meant.

death; the one in the west was pale, while the one in the east was bright. Since Dio is alluding to Vitellius in Rome and Vespasian in Judea, "west" and "east" almost certainly mean a separation of 180º, in which case the pale western sun represents the only mention of an anthelion in classical literature.[34]

Dio and a crowd of Roman observers saw three "stars" (*asteres*) surrounding the sun shortly before the death of Didius Julianus on 1 June, AD 193.[35] These "stars" were immediately associated with the three imperial contenders Severus, Niger and Albinus. The apparition likely consisted of two mock suns and a vertical parherlion, although the occurrence of a triple solar halo cannot be ruled out.

Mock Moons

Only two or three instances of possible mock moons (*luna*, *selênê*) occur in classical literature. The old Roman prodigy lists report "three moons" during the nighttime at Ariminum in 223 BC and "three moons" at an unknown hour in Gaul in 122 BC. The "two moons" in the daytime at Capena in 217 BC were almost certainly not the real moon and a mock moon, because the daytime moon would not shine brightly enough to generate a noticeable paraselene.[36]

Conclusions

All the major phenomena of meteorological optics scientifically recognized today were noticed and recorded in classical antiquity. In addition to the well-known rainbow, mock sun, and solar and lunar haloes, I have identified at least two Bishop's rings, an anthelion, two mock moons and two light crosses. Aristotle's streak was almost certainly a rainbow-like mock sun. What ancient researchers lacked was an adequate theory of these phenomena. Although the rarest phenomena attracted so little attention that no theory was proposed for them, the basic meteorological tetrad of antiquity—rainbow, halo, mock sun and streak—received at Aristotle's hands a unified theoretical treatment, incorporating the idea of reflection from water droplets in a cloud. At least once, the notion of ice crystals was floated for the mock sun.[37] Other ancient researchers discussed refraction, but, judging from Alexander of Aphrodisias' comments on the

[34] [Thphr.] *Sign*. 22 and Arat. 882 explicitly describe ordinary mock suns as located to the "north" and "south" of the real sun. Illogically, the modern authors E.W. Webster in Ross (1931) 372a10 and Tricot (1941) 187 have described the relative positions as "east" and "west."

[35] The *Historia Augusta* wrongly associates this prodigy with the death of Pertinax earlier the same year.

[36] 223 BC: Plu. *Marc*. 4.1; Oros. 4.13; Zonaras 8.20. 217 BC: Liv. 22.1.10; Oros. 4.15; and n. 32. 122 BC: Plin. *Nat.* 2.99; Obseq. 32; Apuleius in Lyd. *Ost*. 4. Böker (1962) 1675 has treated the "night suns" (*sol noctu*) of the Roman prodigy lists as mock moons, but these are almost certainly auroral displays, which Pliny's (*Nat*. 2.100) description and an apparent adherence to an approximately 11-year periodicity both indicate.

[37] Ideler (1836) 321 was the first to pick up on this prescient speculation.

halo, the theory probably involved refraction at the smooth surface of a cloud rather than refraction at the surface of individual water droplets.[38] Thus, some progress was made toward a modern scientific picture, but the ancients' reliance on analogy and the unquestioned paradigm of a mediating cloud remained stumbling blocks for centuries.

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[38] Refraction in antiquity has been discussed for atmospheric phenomena by Ideler (1832) 180–6; Boyer (1956) 383–6 and (1959) 61; Kidd (1988) 498; Ross (2000) 863–71; Lehn and van der Werf (2006) 5624–9; Sider and Brunschön (2007) 166. Although little is known about the ancients' application of refraction to rainbows, haloes and mock suns, a number of less prominent phenomena were interpreted after Aristotle's time in terms of refraction, namely, aerial perspective enlargement of objects, mirage, sun and moon size illusion and below-horizon visibility of the sun, moon and stars. But no equivalent of Snell's law connecting the sines of the angles of incidence and refraction seems to have been discovered during antiquity.

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Table 1. *Solar Haloes and Light Crosses*

Date	*Place*	*Description*	*References*
203 BC	Frusino	Two haloes	Liv. 30.2.12
147	Lanuvium	Two haloes, red and white	Obseq. 20
121	Italy	Rainbow-like halo	Plin. *Nat.* 2.98
114	Italy	Halo	Plin. *Nat.* 2.98
90	Italy	Red halo	Plin. *Nat.* 2.98
44	Rome	Rainbow-colored halo	Vell. 2.59.6; Sen. *Nat.* 1.2.1; Plin. *Nat.* 2.98; Suet. *Aug.* 95; D.C. 45.4.4; Obseq. 68; Oros. 6.20; Lyd. *Ost.* 10b; Zonaras 10.13
AD 94	Greece	Rainbow-like halo	Philostr. *VA* 8.23–5
208	Syria	Halo	Lampr. *Alex. Sev.* 13.5
270	Alexandria?	Halo	Michael the Syrian 6.9; Bar-Hebraeus 8.57
312	Italy	Cross	Eus. *Constantine* 1.28
351	Jerusalem	Cross within rainbow-like halo	Cyril of Jerusalem, *Letter to Constantius* 4.17–23; Philostorgius 3.26; *Chronicon Paschale* Olymp. 282

Table 2. *Mock Suns*

Date	*Place*	*Description*	*References*
525 BC	Egypt?	Two suns	Lyd. *Ost.* 4
206	Alba	Two suns	Liv. 28.11.3; 29.14.3; Claud. *In Eutropium* 1.7
174	Rome	Three suns	Liv. 41.21.13; Plin. *Nat.* 2.99
166	Rome?	Two suns	Cic. *Rep.* 1.20–1
163	Formiae	Two suns	Obseq. 14; Claud. *In Eutropium* 1.7
129	Rome	Two suns	Cic. *Rep.* 1.15–32; *N.D.* 2.14
122	Gaul	Three suns	Obseq. 32
118	Rome	Three suns	Plin. *Nat.* 2.99
104	Picenum	Three suns	Obseq. 43
44	Rome	Three suns, one within a spiky halo	Plin. *Nat.* 2.99; D.C. 45.17.5; Obseq. 68
42	Rome	Three suns	Plin. *Nat.* 2.99; D.C. 47.40.2; Eus.-Jerome *Chronicle* Olymp. 184; Obseq. 70
AD 51	Rome	Three suns	Plin. *Nat.* 2.99; Apuleius in Lyd. *Ost.* 4
69	Rome	Two suns, east and west	D.C. 65.8.1; Lyd. *Ost.* 4; Zonaras 11.16
193	Rome	Three stars surrounding the sun	D.C. 74.14.4–5; Capitol. *Pertinax* 14.3